

Title: Validity and reliability of the Hexoskin® wearable biometric vest during maximal aerobic power testing in elite cyclists

Running head: Hexoskin® validity and reliability

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Abstract

The purpose of this study was to investigate the validity and reliability of the Hexoskin® vest for measuring respiration and heart rate (HR) in elite cyclists during a progressive test to exhaustion. Ten male elite cyclists (age 28.8 ± 12.5 yr, height 179.3 ± 6.0 cm, weight 73.2 ± 9.1 kg, $\dot{V}O_{2\max}$ 60.7 ± 7.8 ml.kg.min⁻¹, mean \pm SD) conducted a maximal aerobic cycle ergometer test using a ramped protocol (starting at 100W with 25W increments each min to failure) during two separate occasions over a 3-4 day period. Compared to the criterion measure (Metamax 3B) the Hexoskin® vest showed mainly small typical errors (1.3-6.2%) for HR and breathing frequency (f), but larger typical errors (9.5-19.6%) for minute ventilation (\dot{V}_E) during the progressive test to exhaustion. The typical error indicating the reliability of the Hexoskin® vest at moderate intensity exercise between tests was small for HR (2.6-2.9%) and f (2.5-3.2%) but slightly larger for \dot{V}_E (5.3-7.9%). We conclude that the Hexoskin® vest is sufficiently valid and reliable for measurements of HR and f in elite athletes during high intensity cycling but the calculated \dot{V}_E value the Hexoskin® vest produces during such exercise should be used with caution due to the lower validity and reliability of this variable.

Keywords:

$\dot{V}O_{2\max}$, athlete monitoring, physiological monitoring, minute ventilation, athlete performance, cycling

INTRODUCTION

Enhanced technology over the last decade has resulted in an increase in the number of wearable devices developed for the collection of human biometric data to enable more appropriately informed decisions in healthcare (15, 17), sports (7), and military environments

(21). These wearable devices use technology such as global positioning systems, heart rate (HR) sensors, blood pressure monitors, accelerometers and plethysmographs to gather biometric data to remotely monitor human activity or to log such data for subsequent investigation.

In sport, software applications have been designed to display the biometric data collected in order to optimise training and performance (1). For example, HR variability, which is a useful objective measure for quantifying training load (16), can be examined using HR monitors or other wearable devices or the information can be downloaded into smartphone software applications (6) to give an indication of the athlete's training and recovery status.

A plethora of consumer health wearable devices are now available which are also being marketed for use by researchers. Thus, investigations into the validity and reliability of such devices is required in various contexts before such devices can be recommended for laboratory use. A commercially available wearable and reusable sleeveless shirt (Lifeshirt®; VivoMetric; Ventura, CA, USA) incorporating a respiratory inductive plethysmography system, along with ECG, pulse oximetry and accelerometer sensors has been shown to have excellent agreement ($r = 0.97$) between the garment and gold standard spirometry for inspiratory minute ventilation (\dot{V}_I) at a mixture of low, intermediate, submaximal and maximal treadmill running exercise intensities (2). Even when comparing \dot{V}_I at maximal exercise alone, the mean difference between the Lifeshirt® and the flowmeter was only ~6% (2). Comparing the same garment (Lifeshirt®) against lab-based monitoring systems, other researchers have also shown excellent agreement in HR and respiratory rate collected at either rest or during exercise (9, 13). Similarly, other wearable devices such as the BioHarness® (Zephyr Technology, Auckland, New Zealand) have been shown to be valid

and reliable at determining respiratory rate during incremental treadmill testing to volitional exhaustion (8).

A relatively new wearable and reusable vest the Hexoskin® (Carré Technologies Inc., Montreal, Canada) produced reliable measures of HR at rest (lying, sitting and standing) and during a submaximal walking test in healthy young volunteers (intra-class correlation between vest and lab-based equipment > 0.96) (20). However, reliability and validity of HR and other physiological parameters measured by this vest at rest or during maximal exercise in elite athletes has not been conducted. Moreover, the unique posture and movements used during cycling could impact the reliability and validity of the Hexoskin® in comparison to the more upright positioning during standing, sitting and lying. The aim of this study was to investigate the validity and reliability of the Hexoskin® vest at measuring respiration and HR in elite cyclists during a progressive exercise test to exhaustion.

METHODS

Experimental Approach to the Problem

This study used a repeated-measures experiment to determine the validity and reliability of a number of physiological variables produced by the Hexoskin® vest. In this study design, each participant performed a progressive cycling exercise test to exhaustion which was repeated after a 3-4 day recovery period. Participants followed a strict testing protocol that was replicated exactly for each test.

Subjects

Ten participants from the Christchurch region in New Zealand participated in this study which was conducted over 1 week in May 2016. Participant inclusion criteria were uninjured

elite male cyclists aged 18 or older currently or just completing training for national or international calibre cycling competitions within the previous 6 months. Participants were recruited from cycle clubs and coaches in the local area and represented elite club and national representatives (see Table 1). Ethical approval for this research has been obtained by the local University Human Ethics Committee (reference 2016-09). All participants were over the age of 18, thus informed voluntary consent was attained from all participants prior to their inclusion in the research.

Procedures

Subject Preparation

Participants reported to the laboratory on two separate occasions over a 3-4 day period. Participants were instructed to present themselves for testing in a rested and hydrated state, having avoided the consumption of alcohol in the preceding 24 hours. Participants were instructed not to change their diet over the study period and to avoid consuming a heavy meal and caffeine containing beverages for 4 hours prior to reporting to the laboratory. Researchers ensured that the aforementioned instructions were adhered to.

Equipment

The Hexoskin® wearable garment was constructed from high-performance fabric (73% polyamide microfibers, 27% elastane) with flexible sensors sewn directly into the fabric. The vests are available in different sizes and for both males and females to ensure the proper fit (3, 4) based on the manufacturer's suggested chest and waist circumferences. In cases where participants were between the recommended vest sizes, waist circumference was used to determine the vest size. The supplied elastic straps were adjusted and positioned to hold both the chest and waist sensors firmly on all participants. The reinforcement of the elastic bands

helped attenuate the possibility of electrode displacement and reduced motion artifacts which could occur with upper body movements throughout the maximal cycle test.

Maximal Cycle Test

Prior to testing, body mass (in cycling gear without shoes) was determined. The athletes used their own pedals and cleated shoes for all testing. The cycle ergometer (Velotron, RacerMate Inc., Seattle, Wash.) was adjusted to the athletes' preferred position, which was then replicated in the subsequent trial. An oxygen mask and a Hexoskin® vest were fitted and sizes were recorded for test-retest consistency. Hexoskin's® instructions were followed to ensure a good fit of the garment and for verification purposes, Bluetooth connectivity was made and real-time data was viewed on a portable electronic tablet device prior to the test. Athletes were informed about the testing protocol being power-ramped and they were instructed to continue cycling until exhaustion. After 10 min of resting data collection while seated stationary on the bike, athletes completed a 5 min warm-up at a low work rate (100-125 W) prior to commencing the test at a workrate of 100 W. All stages were 60 s in duration with an increase in load being 25 W until exhaustion. Athletes were either mountain or road cyclists and to accommodate for individual cadence preferences, the range was set rather wide (~80-100 rpm). Cyclists were instructed to choose a comfortable cadence and maintain that cadence throughout the test. Although not recorded with the other variables, cadence was visible to both participant and researchers to ensure cyclists stayed near their chosen cadence ± 5 rpm. The laboratory temperature was controlled at 15 ± 2 degrees Celsius. The test was terminated when the athlete had reached volitional exhaustion or was unable to maintain cadence. Throughout the test, ventilation and expired gases were collected and analysed every 15 s using a metabolic cart (MetaMax® 3B; Cortex Biophysik, Leipzig, Germany). Oxygen consumption ($\dot{V}O_2$) expiratory minute ventilation (\dot{V}_E) and respiratory frequency (f)

were calculated. Before testing, the gas analysers were calibrated for volume (Hans Rudolph 5530 3-L syringe; Kansas City, MO, USA) and composition (15% O₂ and 5% CO₂).

Maximal oxygen uptake $\dot{V}O_{2max}$ was taken as a 20 s average within which the highest O₂ consumption was measured. Peak power output was defined as the highest workrate the athlete could complete for the full 60 s. HR was measured continuously by ECG (ADInstruments, Colorado Springs, CO, USA) and a Polar HR monitor (RS800CX; Polar, Kempele, Finland).

Data Analysis

HR obtained from a standard 3-lead ECG was acquired continuously at 200Hz using an analogue-to-digital converter (Powerlab/16SP ML795; ADInstruments, Colorado Springs, CO, USA) interfaced with a computer. Breath-by-breath respiratory variables were gathered by the MetaMax® 3B system. HR, \dot{V}_E and f were linearly interpolated at 1 s intervals either by the MetaMax (MetaSoft®) or LabChart software (Human ECG, ADInstruments, Colorado Springs, CO, USA) to coincide with the frequency of data reported by the Hexoskin® garment. Data acquisition using the Hexoskin® vest was recorded at 128 Hz (analog dual-channel) during inspiration and expiration through two strain gauge bands woven into the garment around the chest and waist. Recordings were taken from these sensors to supply an estimation of f and \dot{V}_E , which was calculated as the average of the last 7 completed respiration cycles and output to the data file at 1 Hz. Analog 256 Hz ECG data was collected by the biometric vest and the respiration sensor measured \dot{V}_E in 128 Hz as raw data with 16 bits resolution. During all tests, Hexoskin® data were stored locally in the Hexoskin® device and then uploaded afterwards using HxServices, Hexoskin's® data synchronization desktop software for Windows 8.

With the exception of HR, all data was time-aligned in 1-second intervals and filtered for outliers, which included removing any values greater than 4 standard deviations from the average values for the 60 s period of each workrate and for the entire 5 minute rest period for f and VE data only. For the HR data, on average, 21.83 +/- 14% comprised of outliers (ranging from 2.5% to 52.79%), which were removed so as not to confound the maximal protocol filtering strategy. Workrate stages were selected to provide an overview of the changes at different work intensities (i.e. 25, 50, 75 and 100% of workrate maximum).

The progressive increase in HR with the maximal test, and the large range in erroneous values made a SD-based outlier-detection strategy unfeasible with HR data. Therefore, HR data were examined for suitability based on the previous appropriate data point, whereby any change in HR of >6 beats within one second was assumed to be physiologically unlikely (similar to assumptions by the Polar Heart Rate Monitor software filtering system). Where a HR data point was 6 beats higher or lower than the previous beat, the offending values were highlighted for manual examination and removal.

Statistical Analyses

For the validity analysis, variables gathered from the Hexoskin® wearable vest including HR, minute ventilation and breathing frequency were compared with those of standard laboratory devices (MetaMax® 3B and laboratory ECG) during rest (sitting on the cycle ergometer not pedalling) and during an incremental cycling test to exhaustion. Data were log-transformed prior to analysis to avoid any effects of non-uniformity or error and used a customized statistical analysis (11) based on previously published theory (10) to determine validity. The average of the 5 min rest and 60 s exercise periods (25, 50, 75, 100% workrate maximum in Watts) were used in the analysis. The best measure of validity is the standard error of the estimate (also known as the typical error of the estimate) (19) which is reported along with

other regression validity statistics (Pearson correlation coefficient). Cohen's smallest effect statistics were used to quantify magnitudes of change between variables (12). The standardized typical error (Cohen's d) was given, however, to interpret the magnitude of an error on Hopkin's scale of magnitudes, the error was doubled (18) to 0.2, 0.6, 1.2, 2.0 and 4.0 to indicate small, moderate, large, very large and extremely large effects. A two-sided post hoc power analysis using G*Power (5) revealed that with a sample size of 10, an effect size of 0.5 and an α of 0.05, the power ($1 - \beta$ error probability) was estimated to be low at 29%. There was difficulty finding a large number of high performance cyclists, thus the sample size was small which impacted power. Future studies could help verify findings by using larger sample sizes.

We used a similar approach to analyse the reliability of the Hexoskin® vest (11). Variables measured by the Hexoskin® garment (HR, $\dot{V}_{E, f}$) during moderate-intensity (i.e. 50 and 75% workrate maximum (Watts)) were averaged and compared to the same variables measured by the Hexoskin® 3-4 days later. The within-subject variability (within-subject standard deviation) is analogous to the standard error of measurement which is reported along with the intra-class correlation coefficient. Data is reported as means \pm SD and, where appropriate, the mean effect along with the 90% confidence limits were given.

RESULTS

Participants produced similar peak power outputs and $\dot{V}O_{2max}$ scores during the two incremental cycle tests (Table 1).

[Table 1 about here]

A typical response for the $\dot{V}_{E, f}$ and HR during the test is illustrated in Figure 1.

Figure 1. Sample test response for (A) HR, (B) f and (C) \dot{V}_E comparing criterion values (breath-by-breath system) and Hexoskin® values during a maximal aerobic cycle ergometer test using a ramped protocol (starting at 100W with 25W increments each min to failure).

[Figure 1 about here]

Validity

Differences between the criterion (laboratory) and practical (Hexoskin®) measures for HR and f tended to be small (Table 2). However, as evidenced by the larger typical (standard) error and reduced Pearson correlation coefficient, more error was found in the \dot{V}_E variable between the two devices. The HR recordings from the criterion measures aligned well with those from the Hexoskin® for all workrate stages ($r \geq .98$). The f showed good validity from rest through to 75% W_{\max} ($r \geq .95$) but a moderate discrepancy was detected at 100% W_{\max} (typical error = 6.2%, $r = .91$). The breathing frequency data recorded by the Hexoskin® (Table 2) indicate a mild damping impact, potentially as a result of the inherent tightness of the Hexoskin® garment. Finally, large measurement discrepancies between the criterion and practical measures were found for \dot{V}_E during all stages of the test ($r \geq .69$) except for 25% W_{\max} where the difference was moderate (typical error = 9.5%, $r = .84$).

[Table 2 about here]

Reliability

The test-retest reliability statistics of the Hexoskin® are presented in Table 3. Based on the validity results, it was prudent to assess reliability with the 50 and 75% W_{\max} workrates which provided the most congruency between the criterion and practical measurement devices. The

HR and f variables produced by the Hexoskin® were reliable at these moderate-intensity exercise rates ($r \geq .94$), however the typical error was larger for the \dot{V}_E variable at both workrates (typical error $\geq 5.3\%$, $r \geq .81$). Overall, the typical error between trials for the criterion measurement devices were all small indicating good reliability between trials.

[Table 3 about here]

DISCUSSION

The vast availability of wearable devices has expanded the potential impact of any research using them for data collection. However, completing reliability and validation studies in various contexts is critical prior to laboratory usage of such devices. For example, competitive cycling involves a unique postural positioning and cycling-specific movements which are in stark contrast to those of walking, lying or sitting. This study added to the extant literature as it is the first study to investigate the validity and reliability of the Hexoskin® wearable vest on elite cyclists during a maximal ramped cycle ergometer test. Moreover, the unique posture and movements used during cycling could impact the reliability and validity of the Hexoskin® in comparison to the more upright positioning during standing, sitting and lying.

Sensor data extracted from the Hexoskin® vest was compared to the HR measured by a standard 3-lead ECG as well as the \dot{V}_E and f from the MetaMax® 3B system. The MetaMax® 3B system uses a bidirectional digital turbine to measure the volume and frequency of breathing and previous research has established that the MetaMax 3B has good reliability with intra-device technical error of $<1.0\%$ over a range of metabolic rates (14). Moreover, the MetaMax 3B collects breathing variables directly using a mask covering the nose and mouth and it is considered the gold standard device for such measurements. The Hexoskin®

garment does not provide a direct measurement of breathing variables, rather it derives measurements from an algorithm based on the movement sensor data collected at the chest and abdomen.

The Hexoskin® was found to be valid in comparison to the laboratory ECG for HR and the MetaMax® 3B system for f , but showed lower validity for the \dot{V}_E variable, (typical error 9.5-14.9%) possibly because it was the variable requiring an algorithm for calculation. Although the Hexoskin® was sufficient for measuring everyday activities in healthy adults (20), it was insufficiently reliable and valid when compared to the MetaMax® 3B system for measuring \dot{V}_E in elite cyclists, particularly during high intensity seated cycling. In order to achieve accurate \dot{V}_E and f measurements during recording, the Hexoskin® vest functions best with little or no movement of the garment on the skin and requires continuous conductivity of both the chest and abdomen sensors, which can sometimes be difficult with large amounts of movement fore, aft and laterally. Although body fat was not measured in this study, athlete body mass index ranged from underweight to normal. When measuring people with higher body fat content, perhaps the Hexoskin® would provide better contact between the skin and sensors, thus reducing measurement error and improving reliability and validity. Given the participants were elite cyclists, high aerobic work outputs were achieved during the progressive exercise test which led to high $\dot{V}O_{2\max}$ values (Table 1). Increased aerobic activity led to an increase in upper body movement which is often employed by cyclists while pedalling during bouts of high intensity cycling (e.g. during the 100% W_{\max} stage of the test). This increased torso movement increased the likelihood of the Hexoskin® sensors moving around on the skin, in turn, leading to potential noise signals in the measurements. The higher typical error found in all the variables at rest and in particular in the resting \dot{V}_E variable could be associated with the fact that the Hexoskin® garment logs values at 1 Hz but then averages

the last 7 completed respiratory cycles to the output. Sudden alterations to breathing characteristics which are recorded almost instantaneously with a breath-by-breath system (i.e. MetaMax® 3B) are seemingly delayed with the Hexoskin® garment. Such differences would be diminished during exercise as the subject quickly finds a new steady state to match the exercise workload.. Such differences would be diminished during exercise as the subject quickly finds a new steady state to match the exercise workload. Caution should be exercised when comparing these results to those of a previous Hexoskin® reliability and validity study. Previous research assessed young, healthy individuals rather than elite athletes (20). Also, the previous study measured participants in positions other than cycling (lying, sitting, standing, and walking) (20). Moreover, the present study only measured 10 elite male cyclists on two repeated measures which limits the strength of the results.

To accurately measure reliability, participants are required to be working at the same relative intensity on both test days. To overcome the fact that the cycle test was a progressive test to exhaustion in which the lower and upper exercise intensities can be influenced by external factors such as physiological adjustments to the warm-up, tiredness from previous exercise etc. we chose to use exercise intensities that would be affected less by such extraneous factors (e.g. 50% and 75% of workrate maximum). Using these exercise intensities, we found that the Hexoskin® produced low to moderate typical errors between tests suggesting the Hexoskin® provides adequate reliability at moderate intensity workrates.

The criterion devices commonly used in laboratory settings were also employed for this study and they measured breathing directly at the nose and mouth while HR was collected using sensors on the skin. Similarly, the Hexoskin® relies on conductivity sensors touching the skin of the torso to collect HR. The similar methodology of HR data collection between

criterion devices and the Hexoskin® are elucidated by the good HR validity and reliability.

To generate the \dot{V}_E and f variables the Hexoskin® synthesises data collected from chest sensors through an algorithm. These non-direct breathing measures lessen the Hexoskin's validity and reliability in assessing \dot{V}_E in elite cyclists during a ramped cycle test.

Nevertheless, the Hexoskin® would be well suited for HR and f , whereas laboratory devices would offer increased precision and reliability for \dot{V}_E .

The producers of the garment may consider developing separate algorithms for elite and non-elite subjects and for various sports. As suggested in prior research, more complex algorithms for higher intensity activities could aid in filtering noise signals during measurement (20).

During the cycling tests, subjects at maximal exercise were breathing approximately 170-240 litres of air per minute. The high \dot{V}_E indicated a relatively high error at rest and low and high intensity exercise yet the typical standard error of the estimate increased with intensity. To help reduce measurement error, future research should consider increasing the sampling rate.

PRACTICAL APPLICATIONS

Given the unique nature of these data collection methods, there are implications for practical application. Field practitioners who train elite cyclists likely require accurate HR data and close estimates of breathing capabilities during high intensity cycling. Such practitioners might consider using the Hexoskin® wearable vest with its relative affordability, portability and its versatility to collect real-time data on several athletes simultaneously. On the other hand, researchers or medical practitioners requiring valid and reliable \dot{V}_E are advised to use laboratory devices which are typically more expensive and less portable.

Conflict of interest statement

The authors have no conflicts of interests to declare.

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Table 1. Participant characteristics.

	Test 1	Test 2
Age (yr)	28.8 ± 12.5	28.8 ± 12.5
Height (cm)	179.3 ± 6.0	179.3 ± 6.0
Weight (kg)	73.3 ± 9.2	73.0 ± 8.9
$\dot{V}O_{2\max}$ (ml.kg.min ⁻¹)	61.2 ± 8.2	60.1 ± 7.4
Peak Power Output (W)	410.0 ± 59.2	412.5 ± 55.6
Data are mean ± SD, n=10.		

Table 2. Validity results using average of combined tests comparing Hexoskin wearable vest against the Metamax 3B and laboratory ECG during parallel data collection at rest and during incremental cycle exercise to exhaustion.

Variable	Workrate	Criterion (mean \pm SD)	Hexoskin (mean \pm SD)	Absolute difference (mean \pm SD)	TE	TE% (90% CL)	TE standardized	Qualitative difference	Pearson r
HR (min^{-1})	Rest	65.8 \pm 10.0	65.6 \pm 9.9	0.2 \pm 1.9	2.0	2.8 (2.2-4.0)	0.18	small	0.98
	25% W_{max}	115.4 \pm 13.3	115.1 \pm 13.1	0.3 \pm 2.1	2.2	1.9 (1.5-2.7)	0.16	small	0.99
	50% W_{max}	139.5 \pm 13.2	138.9 \pm 13.5	0.7 \pm 2.1	2.1	1.7 (1.3-2.3)	0.17	small	0.99
	75% W_{max}	164.4 \pm 16.7	163.7 \pm 16.7	0.7 \pm 2.1	2.2	1.3 (1.0-1.8)	0.12	small	0.99
	100% W_{max}	182.8 \pm 13.6	183.5 \pm 15.4	0.7 \pm 4.3	3.8	2.1 (1.7-3.0)	0.27	small	0.99
f (min^{-1})	Rest	16.3 \pm 2.7	14.8 \pm 2.7	1.6 \pm 0.8	0.9	5.8 (4.5-8.2)	0.30	small	0.95
	25% W_{max}	27.1 \pm 5.1	25.7 \pm 5.0	1.4 \pm 1.1	1.2	4.6 (3.6-6.5)	0.25	small	0.97
	50% W_{max}	29.8 \pm 4.4	29.1 \pm 4.5	0.8 \pm 0.6	0.6	2.2 (1.8-3.2)	0.15	small	0.99
	75% W_{max}	37.2 \pm 4.8	36.3 \pm 4.6	0.8 \pm 1.2	1.2	3.5 (2.7-4.9)	0.26	small	0.97
	100% W_{max}	57.1 \pm 8.1	56.4 \pm 7.8	0.8 \pm 3.0	3.1	6.2 (4.9-8.8)	0.42	moderate	0.91
\dot{V}_E ($\text{L} \cdot \text{min}^{-1}$)	Rest	13.5 \pm 2.4	14.5 \pm 2.7	1.1 \pm 2.1	1.8	14.9 (11.6-21.2)	0.72	large	0.71
	25% W_{max}	52.8 \pm 8.7	55.9 \pm 13.0	3.0 \pm 7.5	4.9	9.5 (7.4-13.5)	0.56	moderate	0.84
	50% W_{max}	71.2 \pm 11.5	75.2 \pm 12.4	4.0 \pm 9.5	8.6	11.8 (9.2-17.0)	0.74	large	0.69
	75% W_{max}	107.2 \pm 16.2	110.9 \pm 16.3	3.6 \pm 12.9	12.1	11.4 (8.8-16.3)	0.73	large	0.70
	100% W_{max}	176.2 \pm 25.2	172.9 \pm 31.1	3.3 \pm 23.9	19.6	11.3 (8.8-16.2)	0.73	large	0.71

HR, heart rate; f , breathing frequency; \dot{V}_E , minute ventilation; TE, typical (standard) error of estimate; TE% percent typical error; TE standardized, typical error divided by the SD of the Criterion data; Qualitative difference, qualitative descriptor of the standardized typical error using Cohen's effect sizes, $n=10$.

Table 3. Reliability results of the cardiorespiratory variables produced by the Hexoskin wearable vest and the criterion devices (Metamax 3B and laboratory ECG) over two identical trials at the same submaximal workrate intensity.

Variable	Workrate	Trial 1 (mean \pm SD)	Trial 2 (mean \pm SD)	Absolute difference (mean \pm SD)	TE	TE% (90% CL)	TE standardized	Qualitative difference	ICC
<i>Hexoskin wearable vest</i>									
HR (min^{-1})	50% W_{max}	141.1 \pm 14.6	140.4 \pm 12.5	0.7 \pm 5.8	4.1	2.9 (2.1-5.1)	0.30	small	0.94
	75% W_{max}	164.7 \pm 19.0	164.3 \pm 15.4	0.4 \pm 5.5	3.9	2.6 (1.9-4.5)	0.24	small	0.96
f (min^{-1})	50% W_{max}	29.2 \pm 4.3	29.6 \pm 4.8	0.4 \pm 1.2	0.9	3.2 (2.3-5.5)	0.21	small	0.97
	75% W_{max}	35.8 \pm 4.6	37.4 \pm 4.8	1.5 \pm 1.2	0.9	2.5 (1.8-4.3)	0.19	small	0.98
\dot{V}_E ($\text{L} \cdot \text{min}^{-1}$)	50% W_{max}	74.1 \pm 12.0	73.8 \pm 9.5	0.3 \pm 7.8	5.5	7.9 (5.5-14.6)	0.59	moderate	0.81
	75% W_{max}	109.0 \pm 15.0	109.1 \pm 12.4	0.1 \pm 7.9	5.6	5.3 (3.7-9.7)	0.45	moderate	0.88
<i>Metamax 3B and laboratory ECG</i>									
HR (min^{-1})	50% W_{max}	141.4 \pm 13.9	139.0 \pm 13.2	-2.3 \pm 5.2	3.7	2.6 (1.9-4.5)	0.26	small	0.95
	75% W_{max}	166.0 \pm 19.2	164.6 \pm 15.2	-1.5 \pm 6.3	4.4	3.0 (2.1-5.2)	0.27	small	0.95
f (min^{-1})	50% W_{max}	29.4 \pm 4.5	29.6 \pm 4.8	0.3 \pm 1.6	1.1	4.2 (3.0-6.9)	0.27	small	0.95
	75% W_{max}	36.3 \pm 4.9	37.4 \pm 5.2	1.1 \pm 1.9	1.4	3.8 (2.7-6.3)	0.28	small	0.95
\dot{V}_E ($\text{L} \cdot \text{min}^{-1}$)	50% W_{max}	70.9 \pm 12.1	70.9 \pm 10.9	0.0 \pm 3.8	2.7	3.8 (2.8-6.4)	0.26	small	0.95
	75% W_{max}	106.5 \pm 17.6	106.7 \pm 15.2	0.2 \pm 5.7	4.0	3.7 (2.7-6.2)	0.25	small	0.96

HR, heart rate; f , breathing frequency; \dot{V}_E , minute ventilation; TE, typical (standard) error of estimate; TE% percent typical error; TE standardized, typical error divided by the SD; Qualitative difference, qualitative descriptor of the standardized typical error using Cohen's effect sizes; ICC, Intraclass correlation coefficient, n=10.

